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# Irrigation impacts on minimum and maximum surface moist enthalpy in the Central Great Plains of the USA

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ABSTRACT

Agricultural activities notably alter weather and climate including near-surface heat content. However, past research primarily focused on dry bulb temperature without considering the role of water vapor (dew point temperature) on surface air heat content. When using dry bulb temperature trends to assess these changes, for example, not including concurrent trends in absolute humidity can lead to errors in the actual rate of warming or cooling. Here we examined minimum and maximum surface moist enthalpy, which can be expressed as "equivalent temperature." Using hourly climate data in the Central Great Plains (Nebraska and Kansas) from 1990 to 2014, the averages and trends of minimum and maximum equivalent temperature ($T_{E\_min}$; $T_{E\_max}$) were analyzed to investigate the potential impacts of irrigation. During the growing season, $T_{E\_max}$ averages were significantly higher in irrigated cropland sites compared to grassland sites. This can be explained by increased transpiration linked to irrigation. In addition, $T_{E\_max}$ exhibits a decreasing trend in most sites over the growing season. However, the difference of the trends under irrigated croplands and grasslands is not statistically significant. A longer time series and additional surface energy flux experiments are still needed to better understand the relationships among temperature, energy, and land cover.

## 1. Introduction

It is well known that land cover plays an important role in land-atmosphere interactions and eventually impacts weather and climate (Pielke, 2001; Adegoke et al., 2007; Fan et al., 2015a, b; Xu et al., 2015; Ellenburg et al., 2016). Various observational data-based studies document the notable influence of land cover, including agriculture, on the partitioning of surface energy fluxes and moisture (Adegoke et al., 2007; Betts et al., 2007; LeMone et al., 2007). Modeling studies have also quantified the impacts of land cover (including agriculture) and soil moisture on land surface-atmospheric interactions (Mahmood and Hubbard, 2002; Adegoke et al., 2003; Mahmood et al., 2004, 2011; Notaro et al., 2011; Frye and Mote, 2010; Leeper et al., 2011; Boisier et al., 2012; Suarez et al., 2014).

Hence, if land use and land cover (LULCC) are changed, existing land-atmosphere interactions are also modified and subsequently alter weather and climate (Pielke et al., 2011; 2016; Mahmood et al., 2010, 2014). It is then expected that LULCC driven by irrigation would also impact weather and climate. Some of these impacts are reported in Boucher et al. (2004), Gordon et al. (2005), Douglas et al. (2006, 2009), Sen Roy et al. (2007, 2011), Sacks et al. (2009), Puma and Cook (2010), Mahmood et al. (2008, 2013), Wei et al. (2013), Alter et al. (2015), Harding et al. (2015), and Yang et al. (2017). Application of irrigation for food production changes vegetation cover (e g., irrigated corn, instead of short grass), soil moisture content (low to high), and a variety of other biophysical properties (e.g., albedo, surface length, leaf area index) of the land surface. They eventually modify energy partitioning, physical evaporation, transpiration, and near-surface atmospheric moisture content, among others. Irrigation typically also leads to lowering of dry bulb temperatures due to greater latent energy flux. However, using the dry bulb temperature alone does not capture the total heat content of the air since that temperature measure only accounts for dry heat content (Pielke, 2003; Pielke et al., 2004; Peterson et al., 2011) and yet the dry bulb temperature is used to describe trends in how vegetation affects climate (e.g., Zeng et al., 2017). To address this issue, equivalent temperature ($T_E$) corresponding to moist enthalpy was recommended (Davey et al., 2006; Fall et al., 2010). $T_E$ includes both dry and moist heat content and thus provides a more complete

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measure of changes in the near-surface energy budget.

Recent studies focusing on the United States investigated changes in $T_E$ from 1982 to 1997 (Davey et al., 2006) and 1960–2010 (Schoof et al., 2014) based on observed climate data. Changes in $T_E$ were also investigated based on reanalysis data (Fall et al., 2010). For the first time, mesoscale variations of $T_E$ have been investigated by using Kentucky Mesonet data (Younger et al., 2018). Some of these studies concluded that enhanced ET influences $T_E$. For example, Fall et al. (2010) noted that in areas of higher evapotranspiration (ET) there is larger $T_E$. In addition, they also showed trend differences between mean temperature and $T_E$, which has implications in the evaluation of climate warming. Davey et al. (2006) found that $T_E$ exhibited a relatively warmer trend than temperatures in the eastern United States from 1982 to 1997, and attributed the difference to higher vegetation transpiration. However, their trend and attribution analyses were not focused on irrigation impacts on $T_E$. In addition, these studies focused primarily on mean equivalent temperature (Davey et al., 2006; Fall et al., 2010). Daily extremes of minimum and maximum equivalent temperatures are equally important but were not addressed by in their papers. The latter two measures could be even more important because they represent two specific time periods of a day and capture the range of values during each 24-h period. Although Schoof et al. (2014) discussed maximum and minimum equivalent temperature in their research, all seven stations they used are located at airports or non-rural settings and hence, the role of irrigated agriculture could not be identified [vs. 22 rural stations (8 irrigated, 14 grassland) used in the current study]. Moreover, data homogeneity, particularly related to observation frequency, instrumentation, and station moves are notable in the data set used by Schoof et al. (2014) compared to the stations and data set used in the present research.

Therefore, the objectives for the current study are: (1) to quantify the minimum and maximum $T_E$ averages and trends; and (2) to investigate the effects of irrigation on those averages and trends. The results are based on hourly climate data from the period of 1990–2014 in the Central United States (i.e., Nebraska and Kansas) where irrigation plays an important role in food production. The data and methods used in this study are described in Section 2. The results are presented in Section 3, followed by discussion in Section 4, and summary in Section 6.

## 2. Material and methods

### 2.1. Data sources

Climate datasets were obtained from the High Plains Regional Climate Center (HPRCC, 2015). In this study, the data are from 22 stations where climate observations (temperature and relative humidity) were recorded every hour (Table 1). The length of the time-series are from 1990 through 2014. These stations are well maintained and extensive quality checks were performed. In addition, these stations are part of the regional Automated Weather Data Network (AWDN) and the data quality for Nebraska and Kansas Mesonets are relatively high compared to other in-situ observational networks.

To examine the potential impacts of irrigation on $T_E$ and related variables, we identified stations located in irrigated and grassland areas. For this purpose, we made actual site visits and used gridded satellite data-based products from the National Land Cover Database (NLCD, 2015) which document land cover types in the United States for the years 2001, 2006, and 2011. NLCD data products are used as a general guidance. Subsequently, the land use types for all HPRCC climate stations with sufficiently long periods of observation were identified in the ArcGIS software for each station point. The stations without changes in land cover through 2001 to 2011 served as an initial filter for selecting stations. NLCD data is based on Landsat satellite data and has a resolution of 30 m × 30 m. Subsequently, stations exposed to two major land covers (croplands and grasslands) in Nebraska and Kansas were selected (Fig. 1). We did not use any particular pre-defined buffer zone to determine a site as non-irrigated/grassland. We combined our site visits, general exposure of a station in their respective geographic setting, and guidance from NLCD data to determine whether a station represents irrigated or grassland land cover. Rainfed croplands were excluded because ET differences between grasslands and rainfed croplands are relatively small and the impacts are subsequently expected to be minor as well. In a model-based study, Mahmood and Hubbard (2002) showed that total growing season ET from rainfed cropland was only 2% higher than ET in the grasslands.

**Table 1**
Meteorological stations used for the study.

| Station | State | Latitude | Longitude | Elevation | Land use |
|---|---|---|---|---|---|
| WESTPOINT | NE | 41.85 | −96.73 | 135 | Grassland |
| GARDENCITY | KS | 37.98 | −100.82 | 264 | Grassland |
| ARTHUR | NE | 41.65 | −101.52 | 334 | Grassland |
| DICKENS | NE | 40.95 | −100.98 | 293 | Grassland |
| GORDON | NE | 42.73 | −102.17 | 338 | Grassland |
| GUDMUNDSENRSRCH | NE | 42.07 | −101.43 | 320 | Grassland |
| HALSEY | NE | 41.9 | −100.15 | 251 | Grassland |
| HOLDREGE | NE | 40.33 | −99.37 | 215 | Grassland |
| LEXINGTON | NE | 40.77 | −99.73 | 222 | Grassland |
| ORD | NE | 41.62 | −98.93 | 191 | Grassland |
| COLBY | KS | 39.38 | −101.07 | 294 | Irrigated |
| HUTCHINSON | KS | 37.93 | −98.03 | 145 | Irrigated |
| SCANDIA | KS | 39.78 | −97.78 | 137 | Irrigated |
| TRIBUNE | KS | 38.47 | −101.77 | 336 | Irrigated |
| BEATRICE | NE | 40.3 | −96.93 | 115 | Grassland |
| CENTRALCITY | NE | 41.15 | −97.97 | 158 | Irrigated |
| CHAMPION | NE | 40.4 | −101.72 | 314 | Irrigated |
| ELGIN | NE | 41.93 | −98.18 | 189 | Irrigated |
| MCCOOK | NE | 40.23 | −100.58 | 241 | Irrigated |
| SIDNEY | NE | 41.22 | −103.02 | 401 | Grassland |
| CURTISUNSTA | NE | 40.63 | −100.5 | 239 | Grassland |
| NORTHPLATTE | NE | 41.08 | −100.77 | 262 | Grassland |

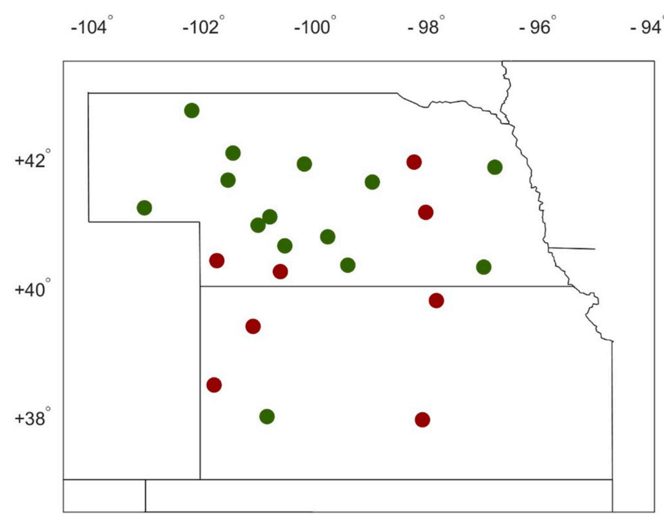


**Fig. 1.** Location of stations included in the study. Maroon and green colored circles represent irrigated and grassland sites, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 2.2. Calculation of $T_E$

At each station, hourly $T_E$ (°C) was calculated using Eq. (1).

$$T_E = T + T_M \tag{1}$$

where $T$ is the hourly temperature observed (°C). $T_M$ is the hourly moisture term of $T_E$ (°C) which is defined as Eq. (2).

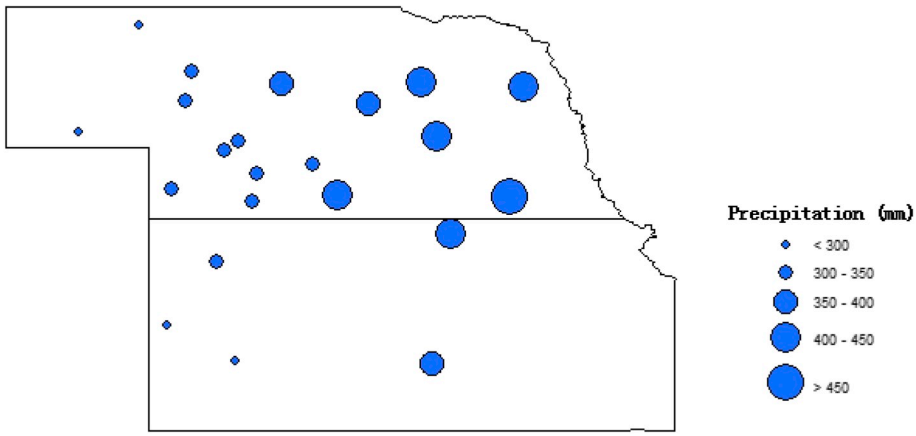


**Fig. 2.** Long-term average precipitation during the growing season (May–September) for each site.

$$T_M = \frac{L_v q}{C_p} \tag{2}$$

where $c_p$ is the specific heat of air at constant pressure, a function of temperature; $L_v$ is the latent heat of vaporization (kJ/kg), which is calculated using Eq. (3); $q$ is the specific humidity (kg/kg), computed by Eq. (4).

$$L_v = 2.5 - 0.0022 \cdot T \tag{3}$$

$$q = \frac{0.62198 \cdot e_a/(p - e_a)}{1 + 0.62198 \cdot e_a/(p - e_a)} \tag{4}$$

where $p$ is atmospheric pressure (millibars) and $e_a$ is actual vapor pressure (millibars). Both were calculated by Eqs. (5) and (6).

$$p = p_0 \exp\left(-\frac{g \cdot M \cdot h}{R \cdot T_0}\right) \cdot 0.01 \tag{5}$$

where $p_0$ is the sea level standard atmospheric pressure (101325 Pa); $g$ is the earth-surface gravitational acceleration (9.80665 m/s$^2$); $M$ is the molar mass of dry air (0.0289644 kg/mol); $h$ is the station elevation (m); $R$ is the universal gas constant (8.31447 J/(mol K)); and $T_0$ is sea level standard temperature (288.15 K).

$$e_a = RH * e_0/100 \tag{6}$$

$RH$ is hourly relative humidity observed (%) and $e_0$ is the saturation water vapor pressure (millibars) with respect to water calculated from Eq. (7).

$$e_0 = (1.0007 + 3.46 \times 10^{-6} \cdot p) \cdot 6.1121 \exp\left(\frac{17.502 \cdot T}{240.97 + T}\right) \tag{7}$$

To explain the trends of $T_M$, dew point temperature ($T_d$) was calculated based on Eq. (8).

$$T_d = \frac{237.3}{\frac{1}{\frac{\log\left(\frac{RH}{100}\right)}{17.27} + \frac{T}{237.3 + T}} - 1} \tag{8}$$

The daily minimum and maximum $T_E$, $T_M$, and $T_d$ for each station (referred to as $T_{E\_min}$, $T_{E\_max}$; $T_{M\_min}$, $T_{M\_max}$; $T_{d\_min}$, $T_{d\_max}$) was calculated on an hourly basis using the above equations. $T_M$ and $T_d$ are used to show the linkage between atmospheric moisture and $T_E$ (Brown and DeGaetano, 2013).

To identify the impacts of irrigation on those variables, this study concentrated on the growing season which was defined as May–September. The average value of each variable was calculated during the growing season and non-growing season as well as the average variables for each month over the growing season. To determine the trends over growing seasons, non-growing seasons and individual months within a growing season, the Theil-Sen analysis (Theil, 1950; Sen, 1968) was used. The trends obtained from this regression analysis are intended to minimize the influence of potential outliers and thus is more robust than the least-square linear regression method.

### 2.3. Identifying irrigation impacts on climate

To determine the irrigation impacts on average moist enthalpy, first the geographic influence was removed. Following an earlier study (Mahmood et al., 2008), a regression relationship was developed for each month of the year for changes in $T_{E\_min}$, $T_{E\_max}$; $T_{M\_min}$, $T_{M\_max}$; $T_{d\_min}$, $T_{d\_max}$ in all grassland sites as a function of longitude (an example for $T_{E\_min}$ was shown in Eq. (9)).

$$T_{E\_min} = \alpha \cdot \text{longitude} + \beta \tag{9}$$

The rationale for the regression analyses is that the grassland sites observed natural near-surface moisture content. These regression models were applied to the irrigated sites for each month and the new calculated variables can serve as geographic-adjusted variables for the irrigated sites (i.e., the weather conditions if the site had grassland). Finally, the difference between observed variables in irrigated sites and adjusted variables (observed – adjusted) shows the impacts of irrigation on equivalent temperatures and related variables. Only longitude was taken into consideration in the regression model because there is a pronounced east-to-west precipitation gradient in the study region which largely determines vegetation gradient and amount of irrigation water applied (Fig. 2). In addition, recent studies (Mahmood et al., 2008, 2013) found the latitudinal gradient of temperature plays a less important role when it comes to irrigation impacts. For irrigation, impacts on trends were not adjusted following Davey et al. (2006). The trends of irrigated and grassland sites were calculated using raw data and we computed the difference of climate extremes (maximum and minimum) between the two land use categories over the study region. Statistically significant differences in these averages and trends over the study region were assessed by a *t*-test setting $p < 0.05$ as a significant level.

## 3. Results

### 3.1. Impacts of irrigation on mean atmospheric moisture and heat content

Fig. 3 demonstrates the difference of observed and adjusted averages for irrigated sites over the growing season. Results indicate that higher $T_{E\_min}$ was observed in six of the eight irrigated sites (Fig. 3a) and $T_{E\_max}$ was also larger in seven of the eight sites (Fig. 3b) over the growing season, compared to their adjusted values with a difference greater than 0.5 °C. Similar results were found for $T_{M\_min}$

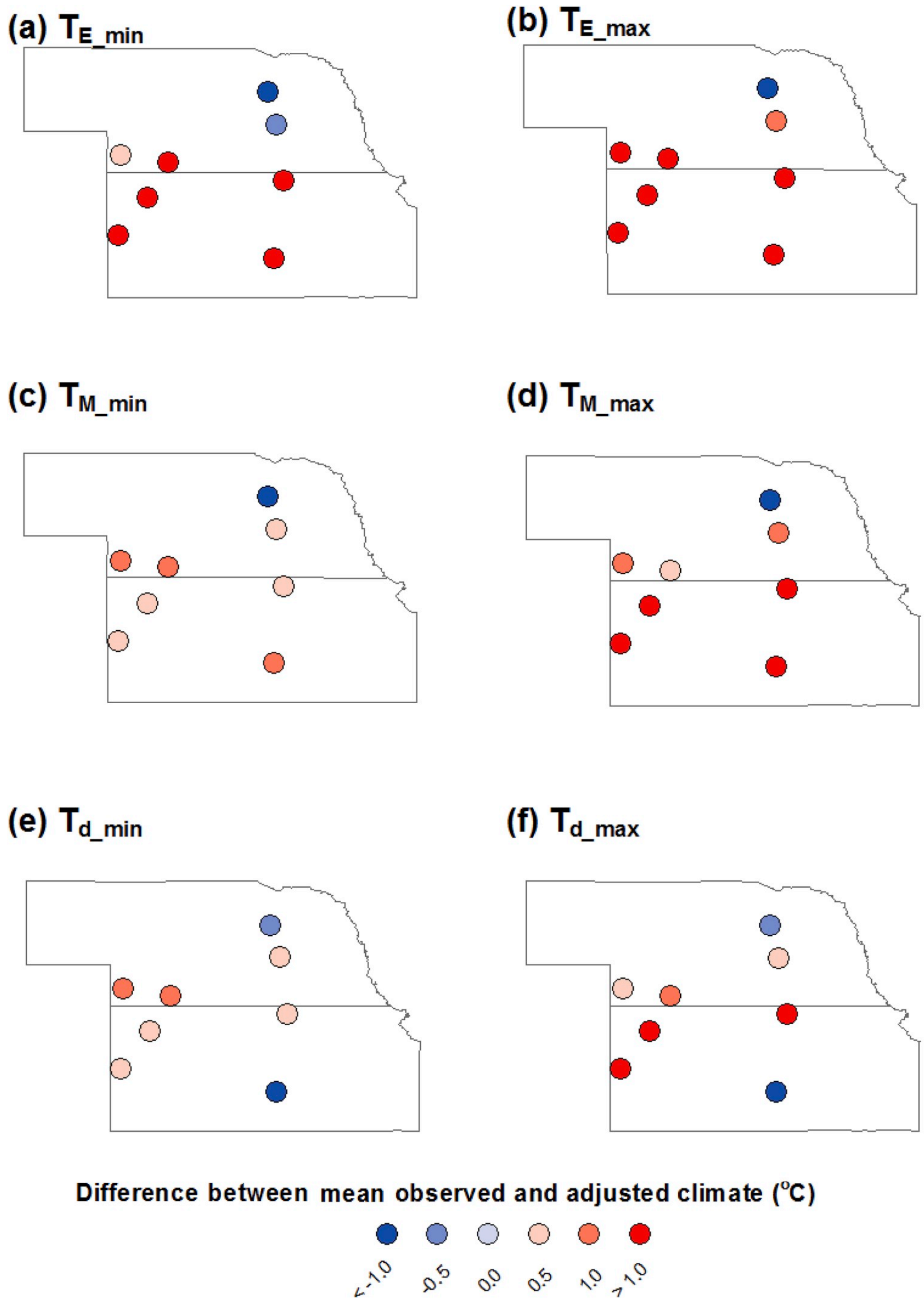


**Fig. 3.** Impacts of irrigation on atmospheric moisture and heat content over the growing season.

(Fig. 3c), $T_{M\_max}$ (Fig. 3d), $T_{d\_min}$ (Fig. 3e), and $T_{d\_max}$ (Fig. 3f). However, over the non-growing season (Fig. 4a–f), the differences between observed and adjusted mean values were less clear than those over the growing season (Fig. 3). For example, only three of the eight irrigated sites show a higher $T_{d\_min}$ (Fig. 4e) and four of the eight show a higher $T_{d\_max}$ (Fig. 4f). Additionally, observed $T_{E\_min}$ (Fig. 4a) and $T_{M\_min}$ (Fig. 4c) were both higher in five of the eight irrigated sites, and $T_{E\_max}$ (Fig. 4b) and $T_{M\_max}$ (Fig. 4d) were higher in six of the eight irrigated sites over the non-growing season period, relative to their adjusted values.

Over the study area, $T_{E\_max}$ and $T_{M\_max}$ under irrigated sites were found to be higher compared with their adjusted values in a statistically significant manner over the growing season (Table 2). The difference between the observed and adjusted value was 2.53 °C (p-value is 0.027) for $T_{E\_max}$ and 1.46 °C (p-value is 0.0435) for $T_{M\_max}$. For variables over the non-growing season, no statistically significant results were found. For each month over the growing season, observed $T_{E\_max}$ was significantly higher than the adjusted averages for each month. The difference was 3.03 °C in May, 2.54 °C in June, 2.36 °C in July, 2.24 °C in August, and 2.5 °C in September. For observed $T_{E\_min}$ irrigated sites were 1.46 °C warmer than their adjusted average values in June. Observed $T_{M\_max}$ and $T_{d\_max}$ were also higher by 1.39 °C and 0.63 °C, respectively, when compared to their adjusted values.

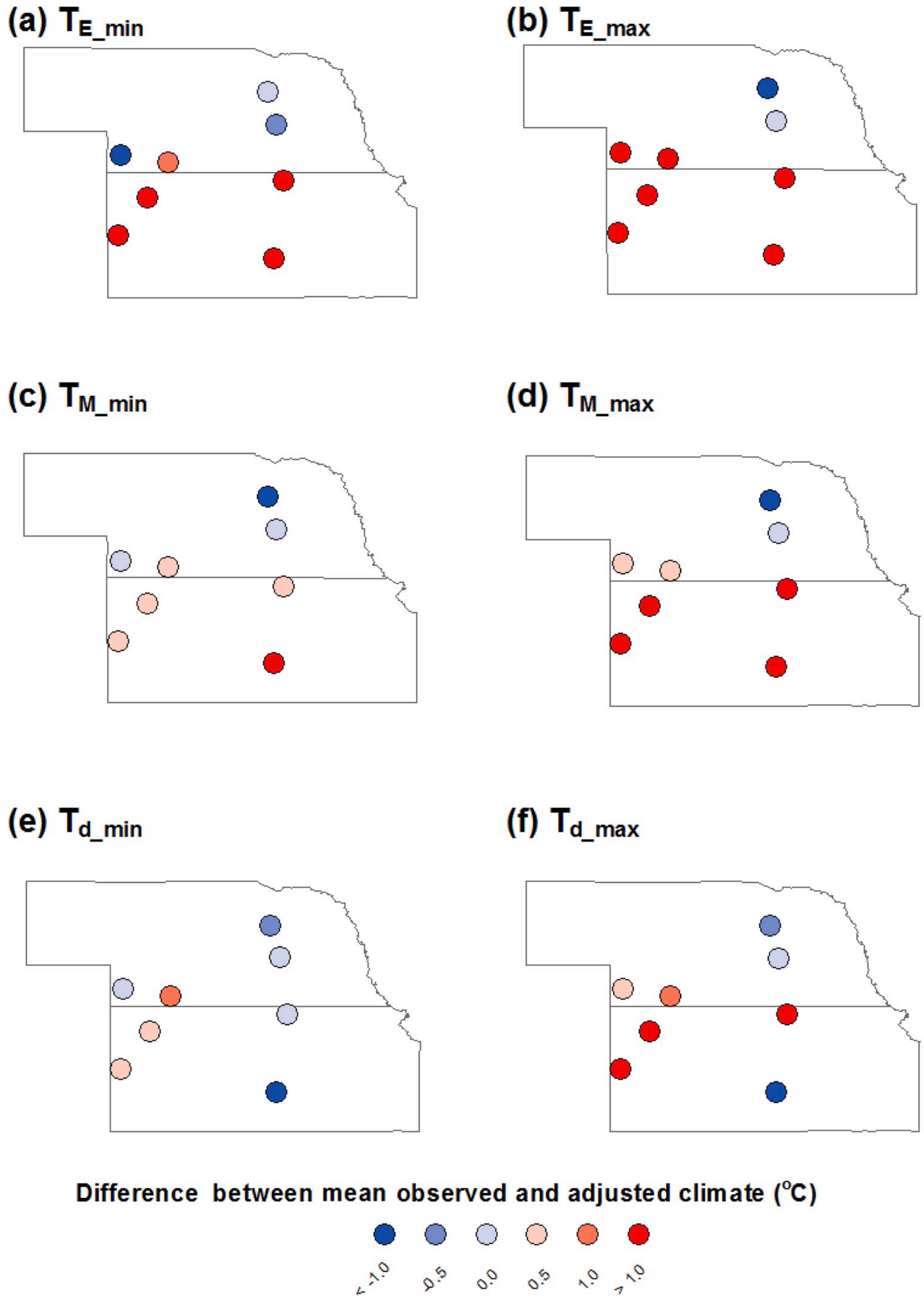


**Fig. 4.** The same as Fig. 2 but for the non-growing season.

**Table 2**
The difference of averages for variables between irrigated and grassland sites, *p*-value of *t*-test is in parentheses. The number in bold font indicates a statistically significant (*p*-value < 0.05) difference.

| Climate | Growing season | Non-growing season | May | June | July | August | September |
|---|---|---|---|---|---|---|---|
| $T_{E\_min}$ | 1.34(0.0504) | 0.98(0.1513) | 1.34(0.0585) | **1.46(0.0412)** | 1.31(0.054) | 1.09(0.0871) | 1.52(0.056) |
| $T_{E\_max}$ | **2.53(0.027)** | 2.12(0.0537) | **3.03(0.0458)** | **2.54(0.0349)** | **2.36(0.015)** | **2.24(0.0314)** | **2.5(0.0286)** |
| $T_{M\_min}$ | 0.26(0.1011) | 0.21(0.2079) | 0.5(0.2116) | 0.12(0.6102) | 0.12(0.6625) | 0.18(0.6026) | 0.37(0.0526) |
| $T_{M\_max}$ | **1.46(0.0435)** | 0.83(0.0641) | 1.8(0.0544) | 1.45(0.0557) | **1.39(0.0322)** | 1.21(0.0896) | 1.44(0.0587) |
| $T_{d\_min}$ | −0.66(0.4843) | −0.65(0.35) | −0.74(0.4567) | −1.05(0.3539) | 0.04(0.8635) | −0.97(0.4592) | −0.57(0.6344) |
| $T_{d\_max}$ | 0.04(0.9662) | −0.03(0.9742) | −0.05(0.9651) | −0.39(0.7444) | **0.63(0.0243)** | −0.24(0.8194) | 0.23(0.8154) |

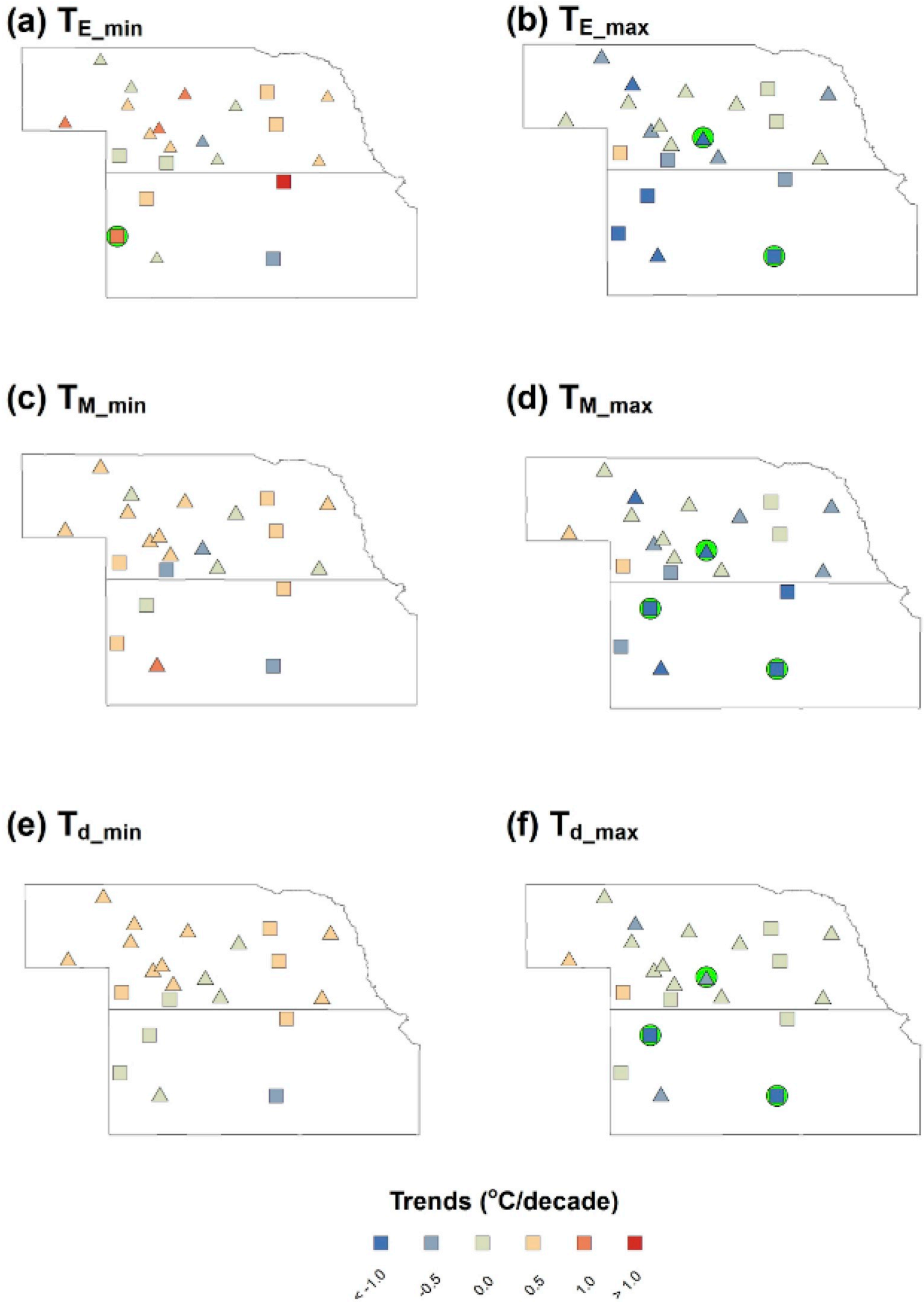


**Fig. 5.** Climatic extreme trends over the growing season. The square indicates irrigated sites and the triangle indicates grassland sites. The stations highlighted with green circle indicate significant trends. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### *3.2. Impacts of irrigation on atmospheric moisture and heat content trends*

Fig. 5a–f illustrates the trends of those variables over the growing season. For most stations, no statistically significant trend was found. $T_{E\_max}$, $T_{M\_max}$ and $T_{d\_max}$ were found to be declined in most sites with a rate of about − 1.0 °C $decade^{-1}$. However, both increasing and decreasing time trends were present for $T_{E\_min}$ and no clear spatial distribution was observed. For $T_{M\_min}$ and $T_{d\_min}$, positive time trends were often observed in Nebraska and negative trends in Kansas. However, over the non-growing season, the majority of stations showed negative trends for all variables (Fig. 6 a – f) except for some sites in the eastern part of the study area where $T_{M\_min}$ (Fig. 6c) and $T_{d\_min}$ (Fig. 6e) increased. For most variables over the study region (Table 3), the trends of irrigated sites were found to be lower than the trends of grassland sites over the growing season, non-growing season, and in the months of May, June, July, and August. September is the only exception where trends of irrigated sites were higher than those under grassland sites. However, it was also noted that the difference of trends between irrigated and grassland sites over the study area are not statistically significant.

## 4. Discussion

Our results document the long-term averages and trends of

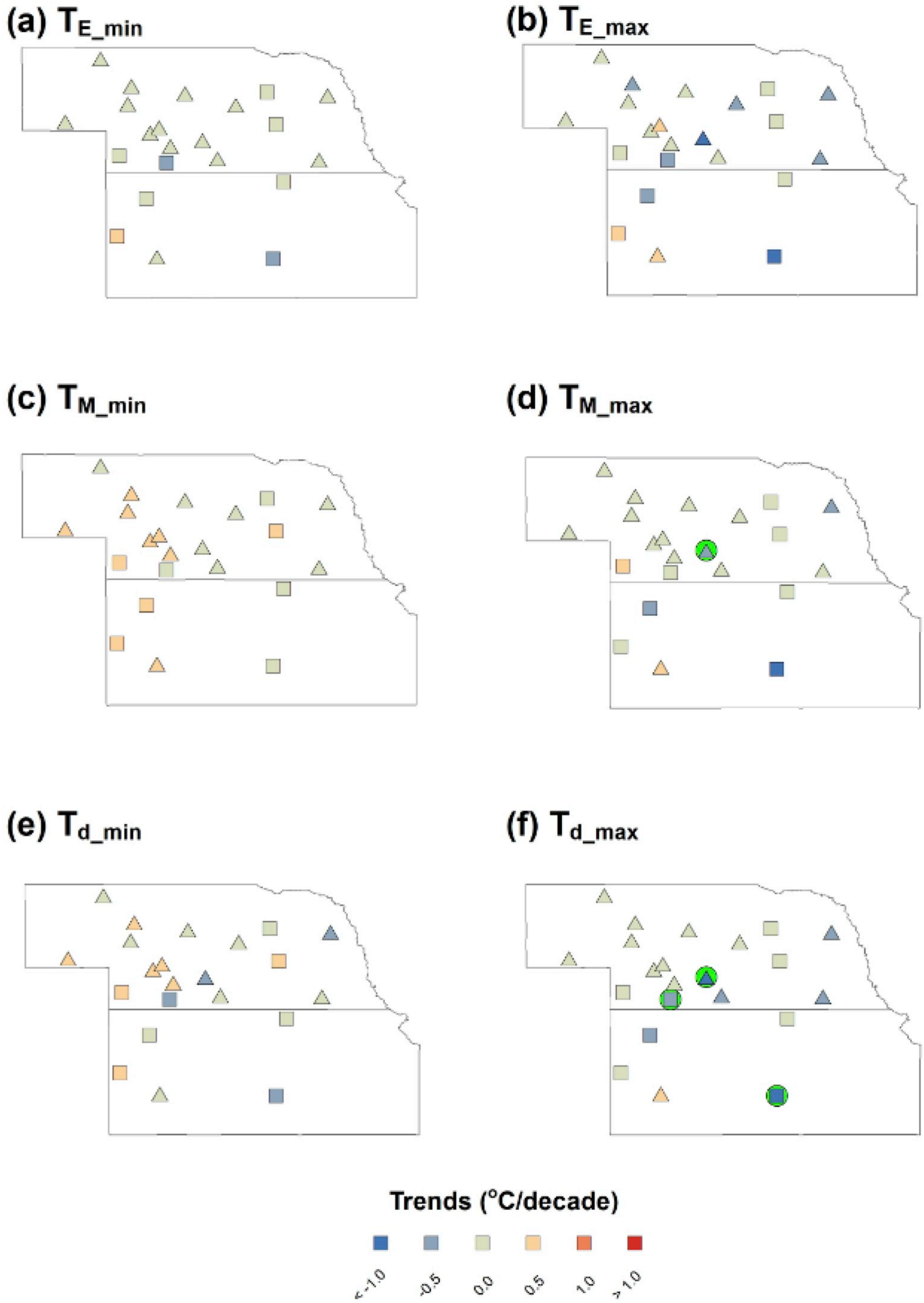


**Fig. 6.** The same as Fig. 5 but for the non-growing season.

**Table 3**
The difference of trends for variables between irrigated and grassland sites, *p*-value of *t*-test is in parentheses.

| Climate | Growing season | Non-growing season | May | June | July | August | September |
|---|---|---|---|---|---|---|---|
| $T_{E\_min}$ | 0.05(0.848) | −0.06(0.6212) | −0.25(0.4022) | 0.22(0.3288) | −0.39(0.2824) | 0.05(0.8578) | 0.43(0.1818) |
| $T_{E\_max}$ | −0.33(0.4602) | −0.01(0.9642) | −0.58(0.1239) | −0.63(0.323) | −1.04(0.1514) | −0.06(0.9114) | 0.18(0.4981) |
| $T_{M\_min}$ | −0.16(0.3666) | −0.01(0.8998) | −0.40(0.0555) | −0.10(0.5912) | −0.30(0.3453) | 0.27(0.2106) | 0.50(0.0611) |
| $T_{M\_max}$ | −0.48(0.2997) | −0.16(0.3566) | −0.68(0.0709) | −0.87(0.1042) | −0.84(0.1525) | −0.25(0.5678) | 0.09(0.7487) |
| $T_{d\_min}$ | −0.2(0.2077) | −0.07(0.6413) | −0.36(0.0703) | −0.08(0.5437) | −0.25(0.2918) | 0.11(0.3659) | 0.37(0.1515) |
| $T_{d\_max}$ | −0.22(0.3028) | −0.15(0.3452) | −0.34(0.1112) | −0.36(0.1571) | −0.35(0.1774) | −0.11(0.5325) | 0.06(0.7262) |

atmospheric moisture and heat content in the Central Great Plains (Nebraska and Kansas) between 1990 and 2014, and the effects of irrigation (Tables 1 and 2). Earlier studies reported impacts of land cover on atmospheric heat content trends (Davey and Pielke, 2005; Davey et al., 2006) and their averages (Mahmood et al., 2008; Younger et al., 2018). During the growing season, it was found that most irrigated sites exhibited higher for $T_{E\_min}$ and $T_{E\_max}$ than grassland (Fig. 3), with some exceptions in northeastern Nebraska, suggesting an influence from irrigation. The differences due to irrigation reach a statistically significant level for $T_{E\_max}$ and $T_{M\_max}$ for the growing season (Table 2), however, a statistically significant difference was not found for the non-growing season (Table 2). This confirms that irrigation influences atmospheric heat content. The higher $T_M$ for irrigated sites is one of the major reasons for higher $T_E$ compared to the grassland sites. Higher $T_M$ under irrigated cropland can be explained by irrigation which increases near-surface atmospheric moisture (Mahmood and Hubbard, 2002; Adegoke et al., 2003).

As to trends, notable changes in near-surface $T_E$ occurred in the study region. The $T_{E\_max}$ over the growing season has been decreased for a number of sites (Fig. 5b) because the moist heat content, i.e., $T_M$, significantly influenced $T_E$. Similarities in the trends of $T_{E\_max}$ and $T_{M\_max}$ (shown in Fig. 5d) were also apparent. The reason for the negative changes of $T_M$ could be due to the different lengths of the time series compared to other studies. Moreover, a change in moisture conditions from those in $T_d$ is believed to be due to the relationship between specific humidity and $T_d$ (Brown and DeGaetano, 2013). $T_{d\_max}$ shows similar trends to $T_{M\_max}$ in terms of spatial distribution of the trend for individual sites. Comparison of the trends between irrigated and grassland sites showed that most of the trends under irrigated sites are slightly lower than grassland sites except in September (Table 3) but more robust test should be further conducted through a longer time series in future studies.

## 5. Summary

In this study, atmospheric heat content averages and trends in Nebraska and Kansas between 1990 and 2014 under two land covers (irrigated and grassland sites) were investigated. The impacts of irrigation on local surface moist enthalpy were evident for the long-term average values. For trends, the impact is less clear. Irrigation resulted in higher $T_{E\_max}$ on average, which can be partly explained by associated increased transpiration. These results are consistent with the findings of Pielke et al. (2004), Davey et al. (2006), Fall et al. (2010), and Younger et al. (2018). Although statistically not significant, $T_{E\_max}$ has a decreasing trend for most sites during the growing season. This is primarily due to a reduction in moisture content that caused lower $T_{d\_max}$ and $T_{M\_max}$ over time. It should be noted that the trends in most variables of irrigated sites were lower than those with grassland over the growing season although the difference was not statistically significant. Further, surface energy flux experiments are still needed to better understand the inter-relationship between temperature, energy, and land cover. This study does highlight that surface air moist enthalpy must be considered to more accurately describe the role of land surface processes on the climate system.

## 6. Conflict of interest

None.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2019.100197.

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